25 Years of Testing the PPN Parameters:
Where do we go from here?

The LATOR Mission

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Outline for the Talk:

- Weak Gravity Field Approximation
  - PPN Parameters
- Present State in Measuring PPN Parameters
  - Recent Results & Methods Used
  - Potential Improvements
- Motivation for Testing Gravity in the Weak Field
  - Goals for the next 5-10 years
  - Possible Experiments & Required Technologies
- The LATOR Mission
  - The Concept
  - The Physics

Weak-Field & Slow Motion Approximation

- Gravitational experiments in the Solar System are well described by the weak-field and slow motion approximation of gravitational field equations
- In the case of General Relativity we have:

$$\sqrt{-g}R_{mn} = -\frac{8\pi G}{c^4}(\hat{T}_{mn} - \frac{1}{2}g_{mn}\hat{T})$$

- Partial differential equations of second order: $\sim \frac{\partial^2 g_{mn}}{\partial x_k{}^2}$
- These field equations are expanded in series with respect to a small parameter (v/c), in fact, $(v/c)^2 \sim GM/c^2r$
- Newtonian limit is given by:

$$g_{00} = -1 + 2U + O(c^{-4}); \qquad g_{0\alpha} = O(c^{-3}); \qquad g_{\alpha\beta} = \delta_{\alpha\beta} + O(c^{-2})$$

The Standard PPN Metric

- Nordtvedt (1968),Will & Nordtvedt (1972) 10 Parameter-PPN Metric:

$$
\begin{aligned}
g_{00} &= -1 + 2U - 2\beta U^2 - 2\xi\Phi_W + (2\gamma + 2 + \alpha_3 + \zeta_1 - 2\xi)\Phi_1 \\
&\quad +2(3\gamma - 2\beta + 1 + \zeta_2 + \xi)\Phi_2 + 2(1 + \zeta_3)\Phi_3 + 2(3\gamma + 3\zeta_4 - 2\xi)\Phi_4 \\
&\quad -(\zeta_1 - 2\xi)A - (\alpha_1 - \alpha_2 - \alpha_3)w^2U - \alpha_2 w^i w^j U_{ij} + (2\alpha_3 - \alpha_1)w^i V_i \\
&\quad +O(\epsilon^3), \\
g_{0i} &= -\frac{1}{2}(4\gamma + 3 + \alpha_1 - \alpha_2 + \zeta_1 - 2\xi)V_i - \frac{1}{2}(1 + \alpha_2 - \zeta_1 + 2\xi)W_i \\
&\quad -\frac{1}{2}(\alpha_1 - 2\alpha_2)w^i U - \alpha_2 w^j U_{ij} + O(\epsilon^{5/2}), \\
g_{ij} &= (1 + 2\gamma U + O(\epsilon^2))\delta_{ij}.
\end{aligned}
$$

- Most measurements of the PPN parameters are done as a by-product of other massive analysis:
  - Spacecraft Doppler and range, planetary microwave ranging,
  - VLBI, satellite laser ranging, etc.
- Designated PPN gravity missions:
  - GP-A (1976), LLR (on-going), LAGEOS (1981-1998), GP-B (2003?), STEP (2005?);

PPN Parameters and Their Significance

Parameter	What it measures relative to GR	Value in GR	Value in semi-conservative theories	Value in fully conservative theories
γ	How much space-curvature produced by unit mass	1	γ	γ
β	How much "non-linearity" in the superposition law for gravity	1	β	β
ζ	Preferred location effects?	0	ζ	ζ
α_1	Preferred frame effects?	0	α_1	0
α_2	–	0	α_2	0
α_3	–	0	0	0
α_3	Violation of conservation of total momentum	0	0	0
ζ_1		0	0	0
ζ_2	–	0	0	0
ζ_3	–	0	0	0
ζ_4	–	0	0	0

C. Will, 1998

PPN parameters quantifying fundamental properties of space-time and are responsible for certain symmetries.

Scalar-Tensor Theories of Gravity

Theory	Arbitrary Functions or Constants	Cosimc Matching in GR	PPN Parameters				
			γ	β	ζ	α_1	α_2
General Relativity	None	None	1	1	0	0	0
Scalar-Tensor: **Brans-Dicke**	ω	ϕ_0	$\frac{1+\omega}{2+\omega}$	1	0	0	0
Generic ST	$A(\varphi),\ V(\varphi)$	φ	$\frac{1+\omega}{2+\omega}$	$1+\Lambda$	0	0	0
Rosen's Bimetric	None	c_0, c_1	1	1	0	0	$\frac{c_0}{c_1}-1$

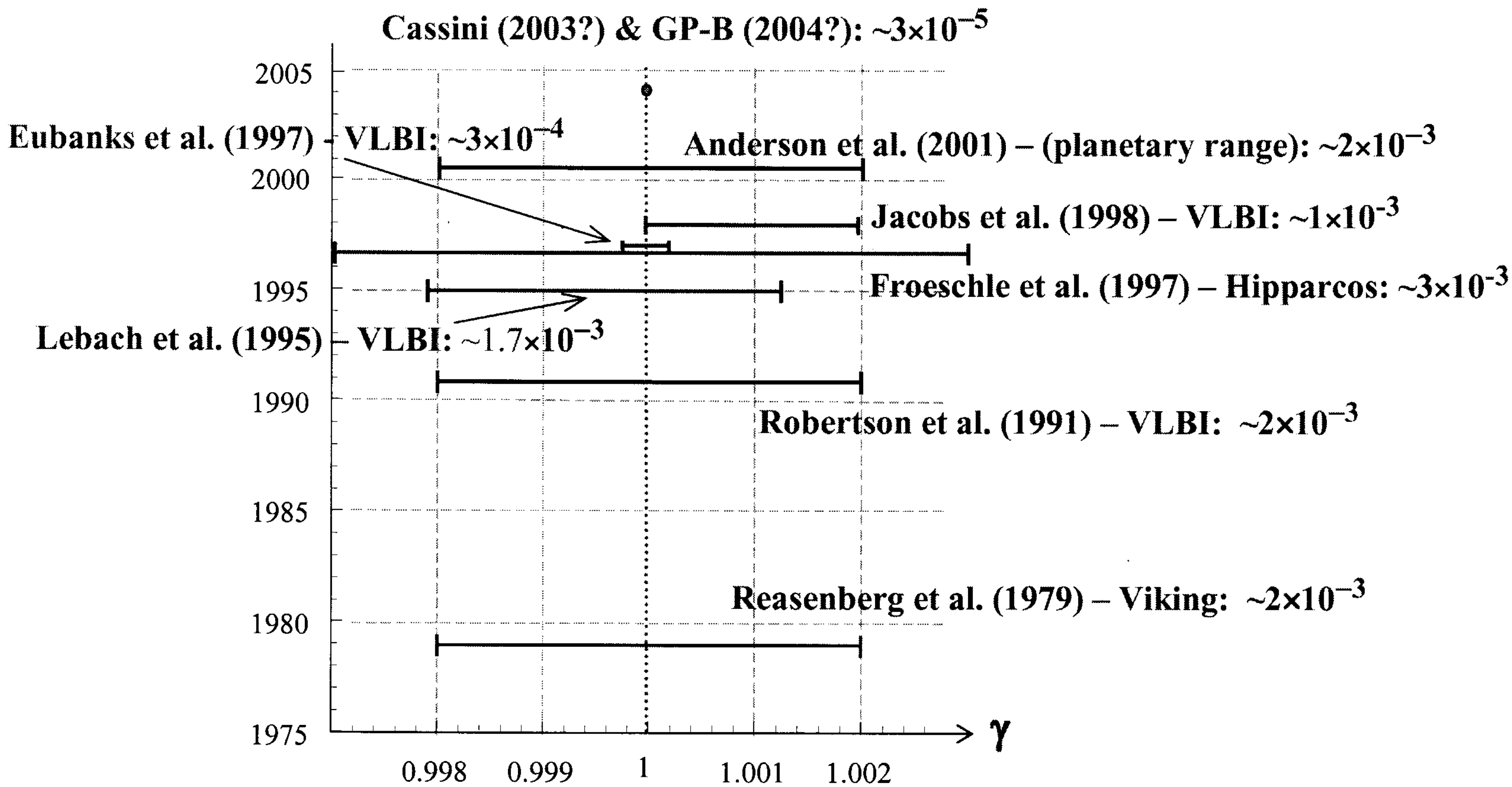
A number of theories are still viable alternatives to general relativity.

Current Limits on PPN Parameters

Parameter	Effect	Limit	Comments	Reference
$\gamma - 1$	Time delay Light Deflection	2×10^{-3} 3×10^{-4}	Viking ranging VLBI	Reasenberg et al. (1976) Eubanks et al. (1998)
$\beta - 1$	Perihelion Shift Nordtvedt Effect & Time Delay & VLBI	3×10^{-3} $\leq 5 \times 10^{-4}$	$J_2 = 10^{-7} \Leftarrow$ helioseismolgy $\eta = 4\beta - \gamma - 3$ assumed & γ from VLBI, planetary	Shapiro (1990) Anderson & Williams (2001) (grand-fit)
η	Nordtvedt Effect* Nordtvedt Effect	1.3×10^{-3} $(2 \pm 8) \times 10^{-4}$	Lunar Laser Ranging $\eta = 4\beta - \gamma - 3$ assumed	Baessler et al. (1999) Anderson & Williams (2001)
ζ	Earth Tides	10^{-3}	gravimetry data	
α_1	Orbital polarization	10^{-4}	Lunar Laser Ranging PSR J2317+1439	Müller et al. (1996) Bell, Camilo & Damour (1996)
α_2	Solar spin precession	4×10^{-7}	Solar alignment with ecliptic	Will (2001)
α_3	Pulsar acceleration	2×10^{-20}	Pulsar $\dot{P}$ statistic	Bell & Damour (1996)
ζ_1	–	2×10^{-3}	Combined PPN bounds	
ζ_2	Binary self-acceleration	4×10^{-5}	$\ddot{P}$ for PSR 1913+16	Will (1992)
ζ_3	Newton's 3rd law	10^{-8}	Lunar acceleration	Bartlett & van Buren (1986)
ζ_4	(Non-independent)	–	$6\zeta_4 = 3\alpha_3 + 2\zeta_1 - 3\zeta_3$	Will (1976)

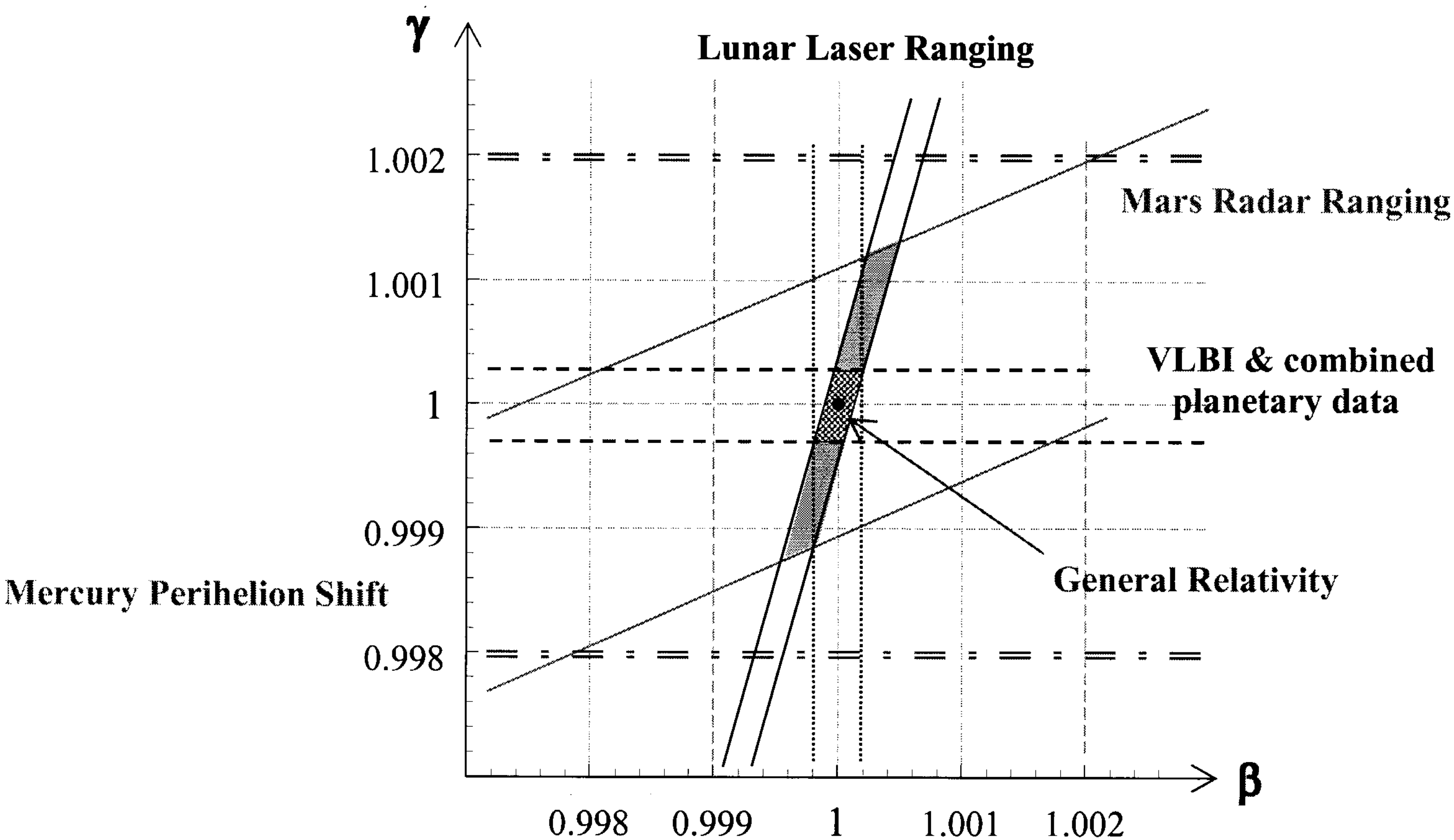
Here parameter $\eta = 4\beta - \gamma - 3 - \frac{10}{3}\zeta - \alpha_1 - \frac{2}{3}\alpha_2 - \frac{2}{3}\zeta_1 - \frac{1}{3}\zeta_2$

Progress in Measuring PPN Parameter γ



25 years of progress in measuring PPN parameter γ: 1979–2004.

25 years of Testing PPN Parameters γ and β



Best Values for PPN Parameters

Parameter	Value	Method	Reference
$\frac{1}{2}(1+\gamma)$	1.000 ± 0.002 1.000 ± 0.002 $0.9996 \pm 0.0017^{d)}$ 1.000 ± 0.005 1.000 ± 0.003 1.0000 ± 0.0003	s/c range (Viking Lander) Geodetic VLBI (10 years, 3×10^5 points) VLBI (3C273B, 3C279 143,154 pts @ 2,8,23 GHz) LLR Astrometric (Hipparcos) VLBI (1979-1996; 1,550,741 points)	Reasenberg et al. (1979) Robertson et al. (1991) Lebach et al. (1995) Williams et al. (1996) Froeschle et al. (1997) Eubanks et al. (1997)
β	0.9999 ± 0.0006 1.003 ± 0.005 $1.0000 \pm 0.00054^*$ $1.00005 \pm 0.00047^*$	LLR LLR LLR & γ fixed @ Viking Lander value LLR & γ fixed @ best VLBI value	Dickey et al. (1994) Williams et al. (1996) Anderson & Williams (2001) Anderson & Williams (2001)
η	-0.0005 ± 0.0011 1.0002 ± 0.0008	LLR, assumes WEP LLR, $\eta = 4\beta - \gamma - 3$ assumed	Dickey et al. (1994) Anderson & Williams (2001)
λ	1.000 ± 0.00075 0.9996 ± 0.0012 1.00000 ± 0.00017	VLBI, LLR, where $\lambda_\odot = \frac{1}{3}(2 + 2\gamma - \beta) + 0.296 \cdot J_{2\odot} \times 10^4$ VLBI, LLR, planetary	Shapiro (1989) Pitjeva (1993) Anderson et al. (2002)
α_0^2 $(1+k_0)\alpha_0^2$	$< 1 \times 10^{-3}$ $< 2.5 \times 10^{-3}$	Combined Solar system data: VLBI, range and Doppler s/c & planets	Damour & Nordtvedt (1993)
$\dot{G}/G$ $\times 10^{-12}$ $[\mathrm{yr}^{-1}]$	$-(2 \pm 4)$ $-(11.0 \pm 10.7)$ (4.7 ± 4.7) < 1	s/c range (Viking Lander) Binary pulsar Mercury radar LLR	Hellings et al. (1983) Damour et al. (1993) Pitjeva (1993) Williams et al. (2001)
$\delta G/G$	-3×10^{-10} AU^{-1} $< 2 \times 10^{-12}$ AU^{-1}	Combined analysis of planetary data LAGEOS, SLR	Nordtvedt (1987) Cuifolini (1993)
Ω_0	≥ 0.018	VLBI	Eubanks et al. (1997)

$^*\eta = 4\beta - \gamma - 3$ assumed

New Discipline: Applied General Relativity

- For the last 30 years GR became an applied engineering discipline:
  - GPS, spacecraft navigation, geodesy, time synchronization, etc.
  - Astrometry is the most demanding discipline for accurate gravity modeling: SIM (~3-10 μas), GAIA (~1 μas)
- The take-away message:
  - WFSM approximation is well mapped to the 1PPN order;
  - <u>Experiments testing the 2PPN order are needed!</u>
- VLBI ($\sim 1\times 10^{-4}$):
  - Number of observations (1.5 M to 15 M → factor of 3)
  - Higher frequencies (need a user for DSN)
- LLR ($\sim 1\times 10^{-4}$): sub-cm accuracies (thermal effects, etc)
- Microwave ranging ($\sim 1\times 10^{-4}$): a designated mission !!!?

Motivation for New Tests

Lagrangian function L_M for the massless scalar is suggested by the low-energy limit of the string theory and it has the form ('Einstein frame') Damour & Nordtvedt (1993):

$$S = -\frac{1}{16\pi G}\int dx^4\sqrt{-g}\Big(R - 2g^{mn}\nabla_m\phi\nabla_n\phi\Big) + S_M[\psi_M, A(\phi)g_{mn}]$$

Expansion $A(\phi)$ around the background value φ_0 of the scalar field leads to

$$\ln A(\varphi) = \ln A(\varphi_0) + \alpha_0(\varphi - \varphi_0) + \frac{1}{2}k_0(\varphi-\varphi_0)^2 + \mathcal{O}(\Delta\varphi^3)$$

Slope α_0 measures the coupling strength of interaction between matter and the scalar.

$$\gamma - 1 = \frac{-2\alpha_0^2}{1+\alpha_0^2} \simeq -2\alpha_0^2, \qquad \beta - 1 = \frac{1}{2}\frac{\alpha_0^2 k_0}{(1+\alpha_0^2)^2} \simeq \frac{1}{2}\alpha_0^2 k_0.$$

A scenario for cosmological evolution of the scalar field:

$$\gamma - 1 \sim 7.3\times 10^{-7}\left(\frac{H_0}{\Omega_0^3}\right)^{\frac{1}{2}} \quad\Rightarrow\quad \gamma - 1 \sim 10^{-5} - 10^{-7}$$

where Ω_0 is the ratio (current density)/(closure density) and H_0 is the Hubble constant.

Murphy et al. (2001) found evidence for time-variablity in the fine structure constant

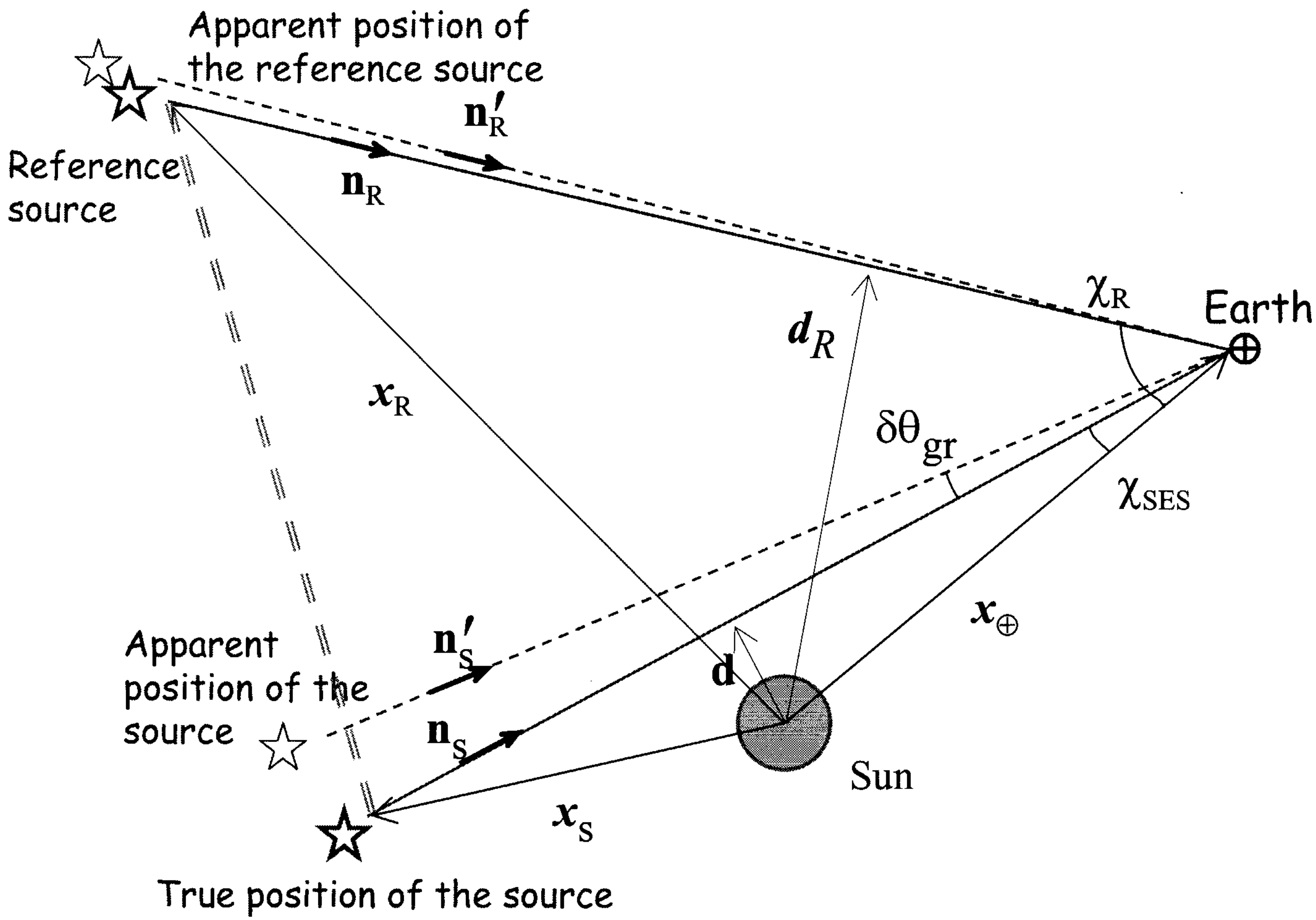
$$\frac{\dot G}{G\,H_0} \approx \eta = 4\beta - \gamma - 3 \quad\Longleftrightarrow\quad \frac{\dot\alpha}{\alpha\,H_0} \sim 10^{-5}$$

provide a tantalizing motivation for testing the SEP parameter η at a comparable level.

Existing & Previously Proposed Concepts:

Goal σ_γ	Project/Method	Comments
$(5-10)\times 10^{-5}$	Cassini/solar conjunction	Two experiments in 2002 and 2003. Ka and X band. Anderson et al (2002)
$(3-7)\times 10^{-5}$	Gravity Probe B Geodetic and Lense-Thirring precisions	Launch in 2003? Buchmann and Everitt (1994)
3×10^{-5} 1×10^{-6}	Mercury Relativity Satellite Mercury Relativity Orbiter	Ashby et al (1995): $\sigma_\beta = 2.3\times 10^{-4}$ $\sigma(J_{2\odot}) = 2.5\times 10^{-8}$, $\delta[\dot{G}/G] = 9\times 10^{-14}$ yr^{-1} Bender et al. (1994): above & laser transponder
4×10^{-6}	Mars Laser Ranging time delay, SEP, 'grand fit'	Murphy et al. (2002): range $\sim \pm 1$ cm, long-range forces, $\delta[\dot{G}/G] = 3\times 10^{-15}$, Mars missions
$\sim 1\times 10^{-6}$	Asteroid Laser Ranging time delay, perehileon precession	Icarus, ...?? Range $\sim \pm 1$ cm, JPL experize, long-range forces, β, $\dot{G}/G$, designated mission
3×10^{-6}	GAIA/μas astrometry	ESA, Launch $\sim$ 2014. Objects $\sim 5\times 10^{7}$
1×10^{-6}	POINTS/μas astrometry light deflection	NASA: work stopped. Reasenberg & Chandler (1989)
1×10^{-7}	Solar Orbit Relativity Test light deflection	ESA: not chosen. Veillet and Stanford (1994) Laser transponder/receiver
$\sim 10^{-7} - 10^{-9}$	LATOR I: optical interferometery 2PPN order light deflection to $\sim 0.2\mu$as	MIDEX Proposal: Shao et al. (1994), JPL experts Optical interferometry & Laser transponder/receiver

LATOR: Relativistic Deflection of Light



Both LATOR (Shao et al., 1998) and SORT (ESA, 1998) are similar to VLBI Experiments with Deflection of Light by the Sun

LATOR: Laser Astrometric Test of Relativity

- Shao et al. (1994) proposed a space-based experiment to measure the gravitational deflection of light by the Sun.
- Experiment uses:
  - Two spacecraft @ 1AU, heliocentric orbit & Laser;
  - A ground-based optical interferometer to measure angles between the two spacecraft to accuracy of ~2 μas.
  - Laser ranging to spacecraft:
    - Interplanetary Laser transponders with accuracy ~10 cm;
    - Or Radio Doppler methods might also be used for ranging.
- Geometric redundancy will allow to measure:
  - PPN parameter γ: $\sim 10^{-6} - 10^{-8}$;
  - 2PPN order light deflection & frame dragging effects.

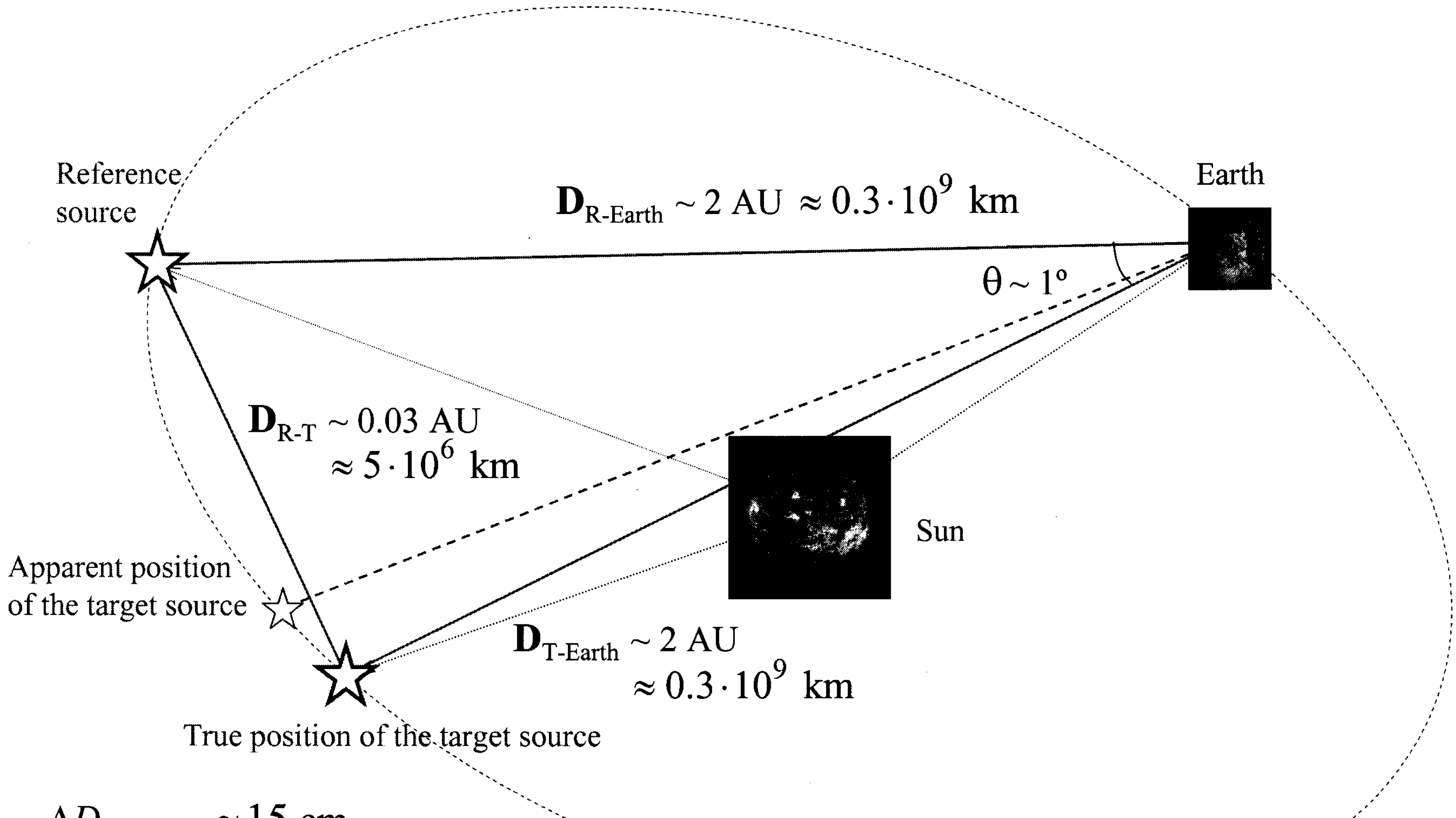
LATOR: Laser Astrometric Test of Relativity

A MIDEX-class ($180M) LATOR experiment uses:

- Two spacecraft @ 1AU, heliocentric orbit & laser transponders;
- An optical interferometer to measure angles between the two spacecraft to accuracy ~0.02 μas (needed 1% of 3.5 μas).

1. Laser transponders for pointing and range at 2AU.
   - Interplanetary Laser transponders with accuracy ~3 cm;
   - Target acquisition with solar background.
2. Angle Measurement Accuracy
   - Laser Interferometer on ISS with ~100m baseline;
   - 0.02 μas => 0.1 picorad ~10pm.
   - SIM demonstrated laser metrology repeatability <10pm (~0.03 Hz)

LATOR: Relativistic Deflection of Light



$$\Delta D_{\text{R,T-Earth}} \approx 15 \text{ cm}$$

$$\Delta D_{\text{R-T}} \approx 0.3 \text{ cm}$$

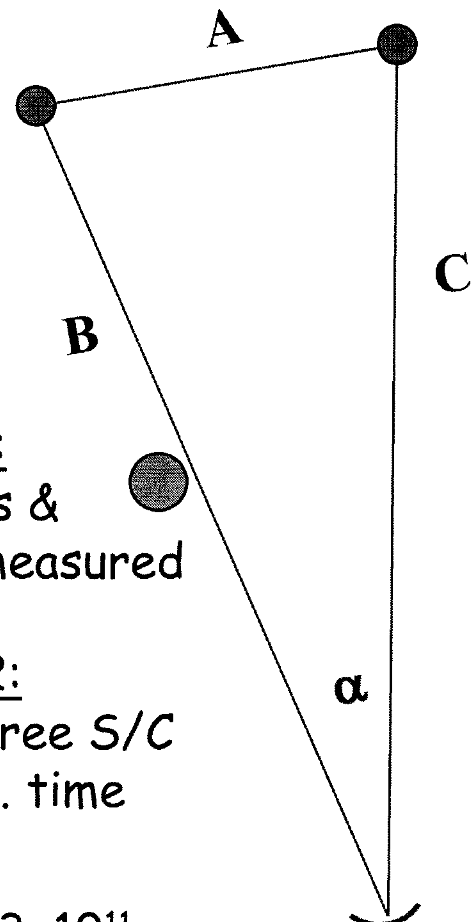
Geometric redundancy will allows for accurate measurement of:
Relativistic gravitational light deflection to 1 part in 10^9.

Sizes of the effects

	Analytic Form	Value (μas)	Value (pm)
First Order	$2(1+\gamma)\frac{M}{R}$	1.75×10^6	1.537×10^{21}
Finite Distance to Earth	$-\frac{1}{2}(1+\gamma)\frac{M}{R}\frac{R^2}{r_E^2}$	-9.5	
Frame-Dragging	$\pm\frac{1}{2}(7\Delta_1+\Delta_2)\frac{J}{R^2}$	± 0.7	
Solar Quadrupole	$2(1+\gamma)J_2\frac{M}{R}$	0.2	
Second Order	$([2(1+\gamma)-\beta+\frac{3}{4}\Lambda]\pi-2(1+\gamma)^2)\frac{M^2}{R^2}$	3.5	65.8

SIM demonstrated laser metrology repeatability <10pm

Several Different Measurement Options



<u>Option 1:</u>
3 lengths &
1 angle measured

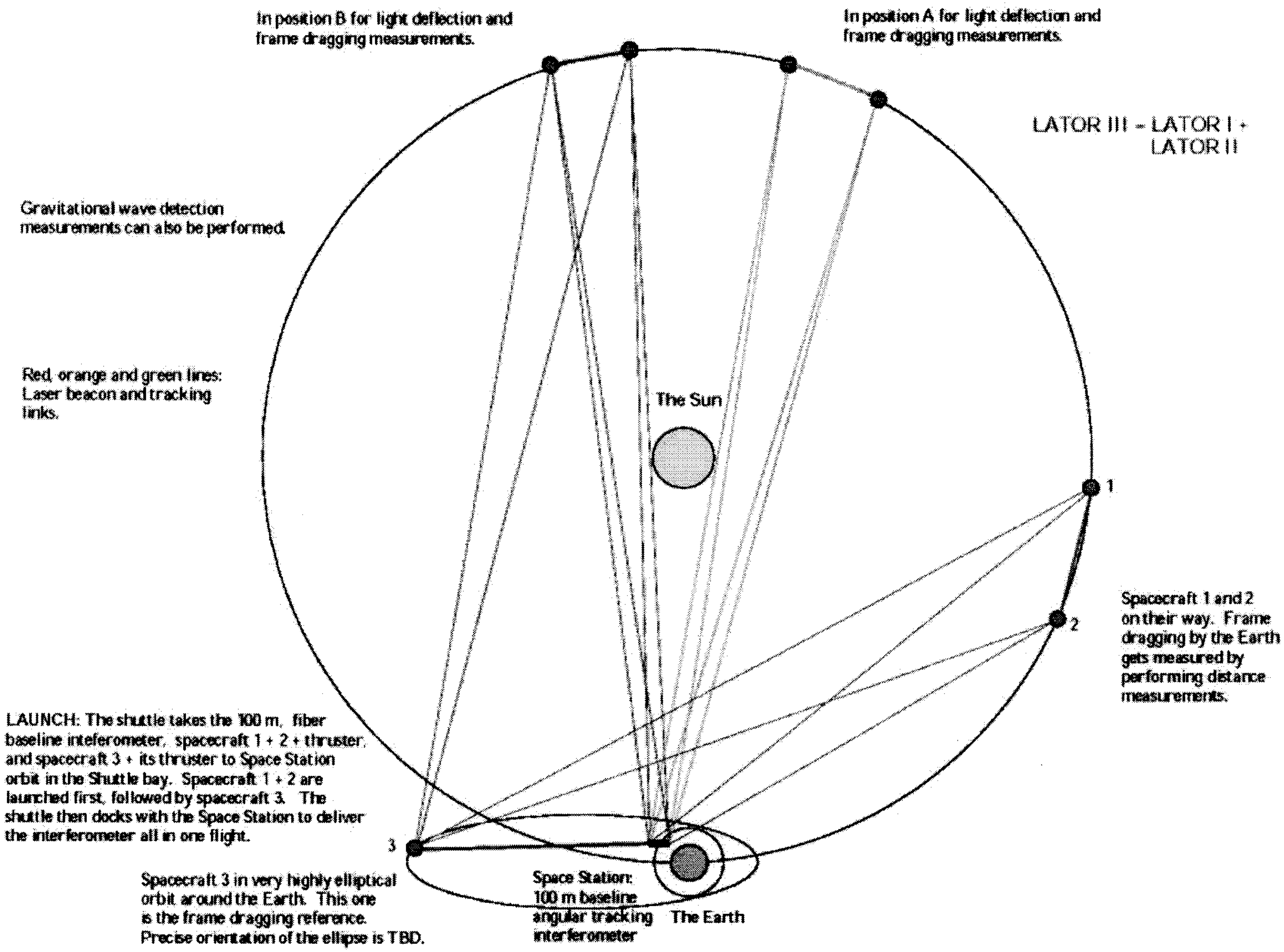
<u>Option 2:</u>
2 drag free S/C
Angle vs. time

B ~ C ~ 3×10^{11}m
A is measured to ~3cm

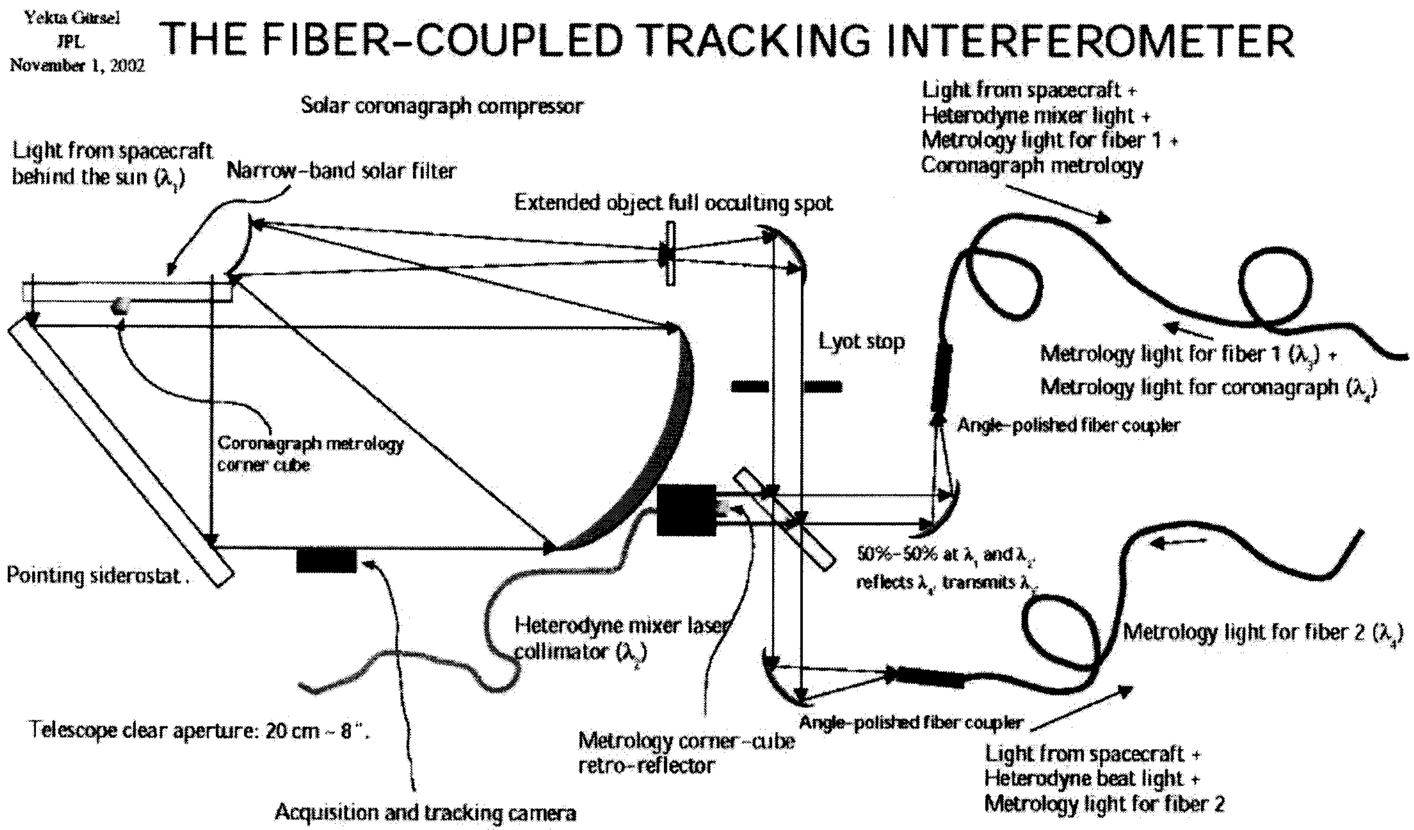
<u>Angle Measurement Options:</u>

- Ground based 10km interferometer is atmospheric limited ~0.2 μas
- Laser Interferometer on ISS:
  - ~100m baseline;
  - $(M/R)^2$ term ~3.5 μas;
  - 0.02 μas => 0.1 picorad ~10pm.
- SIM demonstrated laser metrology repeatability <10pm (~0.03 Hz)
- Highest accuracy with all-in-space experiment
- There is another option that utilizes 4 s/c in the Earth's vicinity

The LATOR Experiment



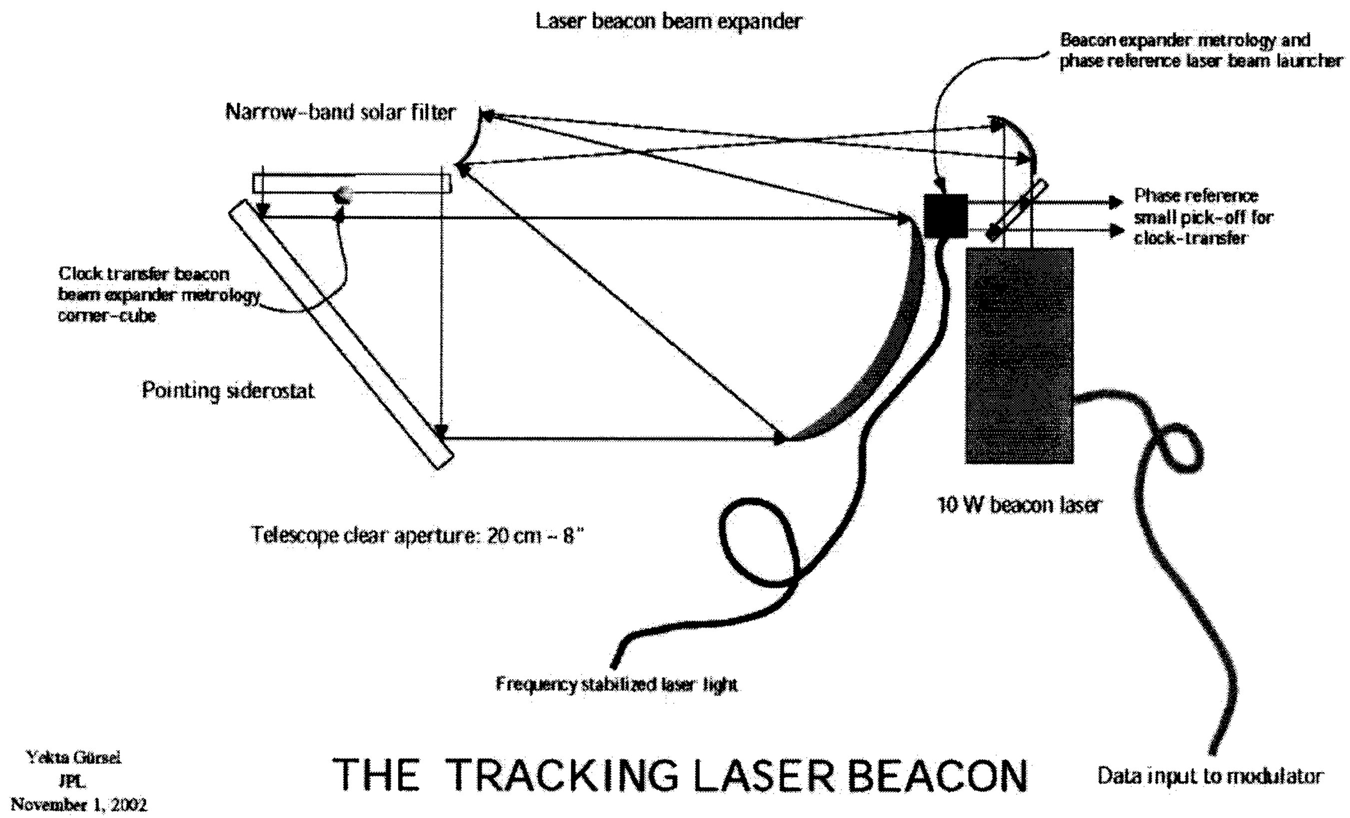
LATOR III Experiment (2)



ANGLE TRACKING INTERFEROMETER RECEIVER ELEMENT: There are a total of four of these receivers looking at spacecraft 1 and spacecraft 2 in pairs, with members of each pair separated by 100 m at each end of the station. In addition to these, the interferometer consists of the beam combiner and a pair of linked laser beacons. The laser beacons are only for direction finding for the spacecraft (Earth location beacon) and data transmission.

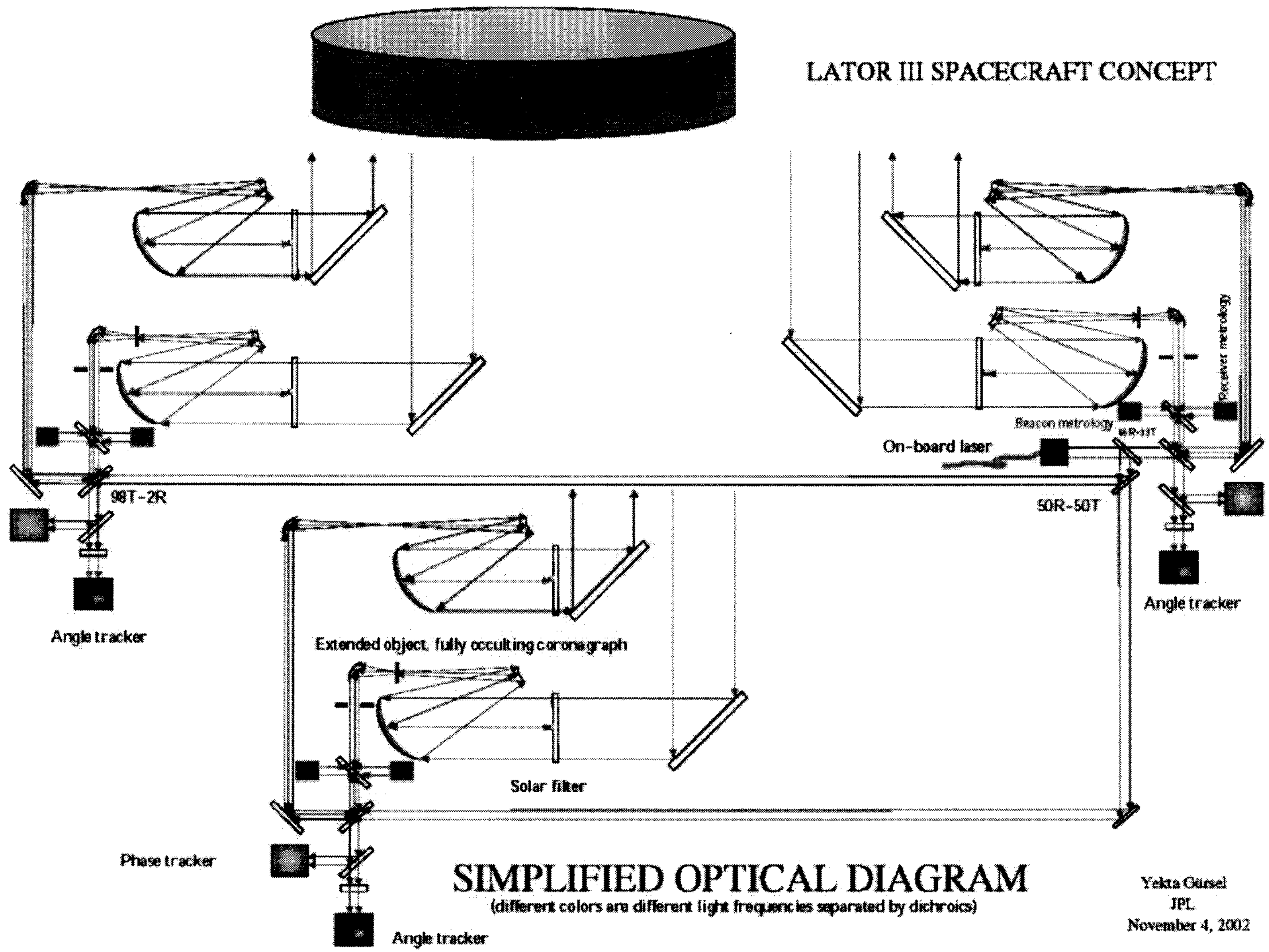
LATOR III Experiment (3)

THE FIBER-COUPLED TRACKING INTERFEROMETER



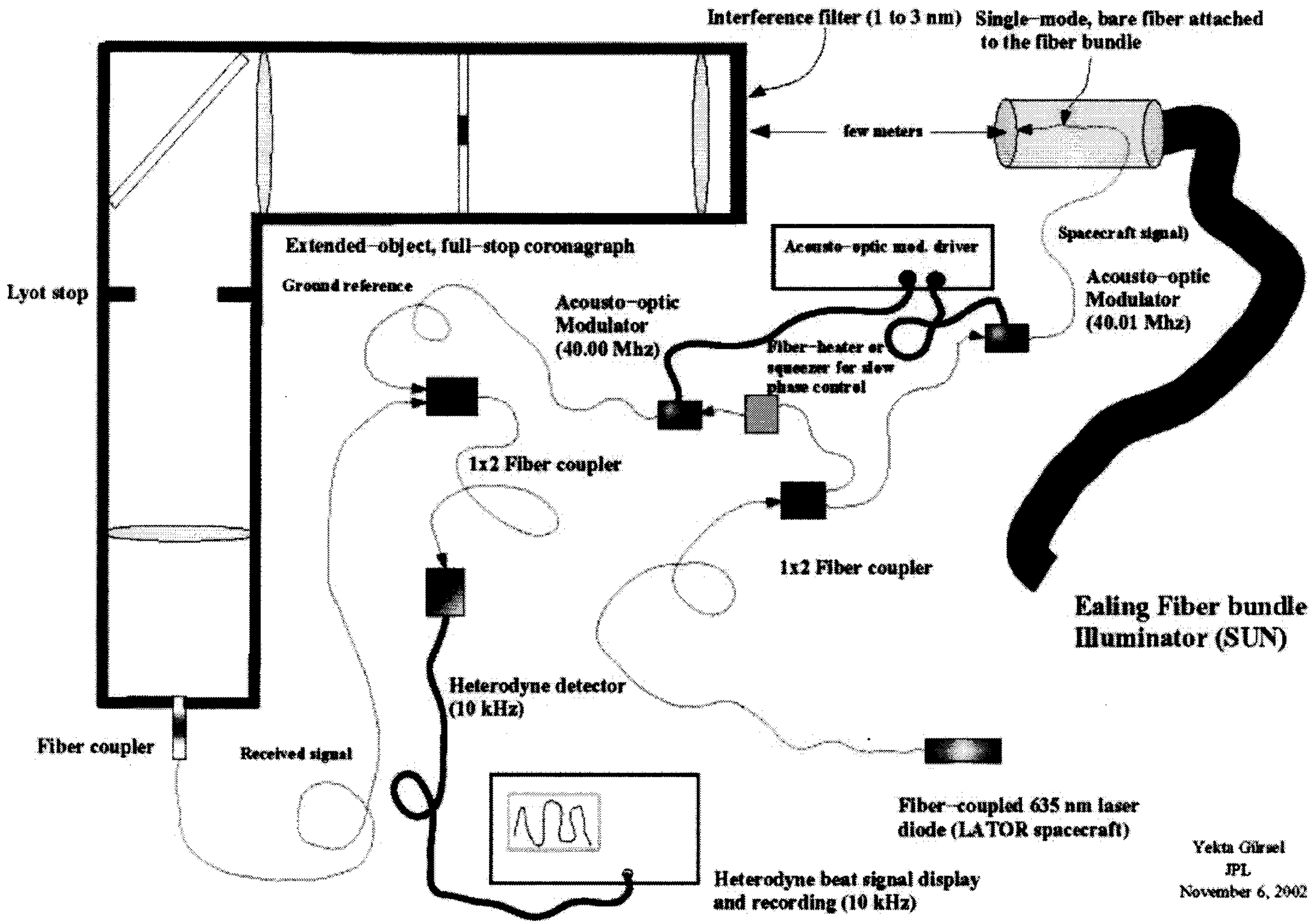
THE TRACKING LASER BEACON

LATOR III Experiment (4)



LATOR III Experiment (5)

LATOR III Technical Demonstration



Why is LATOR Potentially Orders or Magnitude more sensitive?

- Optical vs. Microwave:
  - Solar plasma effects decrease as λ^2: from 10cm (3GHz) to 1 μm 300 THz is a 10^{10} reduction in solar plasma optical path fluctuations. (As compared to microwave probes of the solar gravity.)
- Orbit determination:
  - Drag-free satellites are needed by LISA;
  - The use of a redundant optical truss is an alternative to ultra-precise orbit determination. LATOR is insensitive to S/C buffeting from solar wind and solar radiation pressure (compare to Cassini/LLR/GP-B)
- Potential for a low cost experiment:
  - Optical SNR is very high, 100's mW lasers with freq stability and lifetime already developed for telecom and flight qualified for SIM.
  - Optical apertures in the 5cm to 10cm range sufficient;
  - Options exist for no motorized moving parts, final precise alignment options include electro-optic

LATOR offers a very good science!

- LATOR will achieve accuracy 4 – 5 order below currently available by measuring the 2PPN order relativistic deflection of light
  - PPN parameters γ: $\sim 10^{-7} - 10^{-9}$;
  - A number of theories of gravity will be tested in a new regime.
- Other interesting contributions:
  - Relativistic frame-dragging effect;
  - Solar system research:
    - Solar physics: solar J2; frame-dragging effect, mass, atmosphere;
    - Solar system bodies: masses, distances;
  - VLF Gravitational Waves?
  - Verification of the matched asymptotic expansion technique.
- Gravitational physics community support/endorsement: National Academy of Sciences report for Space Science in 21st century

2nd Order PPN test of relativity is a very good science!

Conclusion: New Physics & Valuable Technologies

- Synergy with current and future JPL missions and strategic goals:
  - SIM, LISA, Starlight;
  - Optical interferometry;
  - Precise navigation and communications;
  - Gravitational physics and computational data analysis center (potential users LIGO, LISA, LATOR, etc?)
- LATOR will utilize/improve existing technologies:
  - Sub-picometer-class metrology;
  - Precision optics and structures;
  - Milli-Kelvin thermal control.
- LATOR will open a window to address new Grand Challenges

The expected results are important; the mission should be done.